GaAs RFICs FOR MOBILE TELEPHONE APPLICATIONS -- A REVIEW

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ABSTRACT

By far the single largest application for GaAs RFICs in commercial/consumer platforms is in mobile telephone handsets covering several standards such as analog AMPS, digital PCS TDMA and CDMA, Japanese PHS, European GSM, DCS1800 and DECT. However, a considerable number of technologies are potentially available for RFIC designs such as Si BiCMOS, Si LDMOS, SiGe, GaAs MESFET, GaAs pHEMT, AlGaAs and InGaP HBT. After a brief review of competing technologies, emphasis in this paper is placed on describing a number of examples of GaAs RFIC designs used in present telephones concentrating on the highest performance parts required in PCS and dual-band CDMA platforms. Integration of receive and transmit functions, providing substantial area reduction and integration improvement for next generation platform applications, will be described such as a PCS transmitter module containing GaAs upconverter, driver amplifier and power amplifier ICs. Technologies are compared for future higher levels of integration allowing the production of "one-chip radios".

INTRODUCTION

GaAs RF integrated circuits are used in a number of high volume applications such as direct satellite television (DBS) receivers at 12 GHz, wireless local area network (WLAN) transceivers at 2.45 GHz and 5.8 GHz and TV tuners from UHF to 1 GHz. By far the single largest application for GaAs RFICs is for a variety of mobile telephone handset applications covering several standards such as analog AMPS, digital PCS TDMA and CDMA, Japanese PHS, European GSM, DCS1800 and DECT. Estimates for GaAs ICs for such telephone platform applications by the year 2000 are of the order of 300 million pieces. Such telephones are being driven by lower prices, smaller sizes and higher functionality. The latter includes so-called dual-mode (cellular AMPS and CDMA, for example); dual-band (cellular AMPS and PCS CDMA, for example) as well as tri-mode (GSM, PCS and satellite coverage such as Iridium^{SM} or Globalstar^{TM}, for example). Such RFICs are used in the "front-ends" of telephones for low-noise amplifiers, high intercept point mixers in receivers, high linearity upconverters and driver amplifiers as well as high efficiency/high linearity power amplifiers in transmitters (Figure 1). Price pressures are severe – for example, an AMPS power amplifier that was priced at $8 three years ago is now less than $3 and will be priced at $1 by the year 2000. This price pressure taxes the ingenuity of designers to produce very small die in low-cost packages that can maximize the number of parts per wafer.

A considerable number of technologies are potentially available for RFIC designs such as Si BiCMOS, Si LDMOS, SiGe, GaAs MESFET, GaAs pHEMT, AlGaAs and InGaP HBT. However, GaAs-based ICs have been able to show the most substantial volume production in this market application. This is because of a number of advantageous performance reasons including low consumed current, high linearity, high gain per mA of current etc.

GaAs FOR RECEIVE AND TRANSMIT FUNCTIONS

Figure 2 shows the schematic diagram of a typical cellular AMPS or PCS telephone RF front end. GaAs can be used for both receive and transmit functions. The most popular use of GaAs ICs is in the transmit sections of telephone boards. For example, many platforms today use GaAs MESFET upconverters such as the one shown In Figure 3 giving good conversion efficiency and high linearity in CDMA mode at low DC currents. MESFET based integrated upconverter/driver amplifiers, both for single and dual-band applications are also available for next generation platforms. GaAs MESFET, pHEMT and HBT solutions dominate power amplifier needs. Table 1 shows a comparison between power amplifiers where the data clearly indicates that GaAs discrete and IC solutions dominate. Figure 4 shows a typical pHEMT high linearity, high efficiency PA that provides 30 dB gain, 50 dBc ACPR and 40% PAE in PCS under CDMA loading. The IC is less than 2 sq. mm. in area and is housed in a low cost air-cavity plastic package with integral heat-sink and ground plane. Such amplifiers can use "smart" negative gate voltage to reduce DC current consumption when the PA is delivering lower than its maximum output power, often the case in digital telephone systems.

Typically, in present telephone platforms the LNA in the receiver front-end is built using discrete transistors since these can be very low cost. However, GaAs RFICs are becoming more popular. Firstly, this is because basic functions (such as integrated mixers/LO drivers) can be produced in very small die areas packaged in very small outlines (such as SOT-23) and sold for very low prices. Secondly, the technology easily allows the complete receive function to be provided by an integrated solution that offers low SSB noise figure, adequate IIP3 at low DC currents (for both in-band and out-of-band signal de-sense) with high efficiency down conversion. Figure 5 shows a fully integrated dual-mode AMPS/CDMA ASIC employing E/D MESFET technology that is packaged in a SSOP outline (Brunel et al, 1).

DRIVERS FOR TELEPHONE COMPONENT SELECTION

If the technologies being considered for telephone platform applications are volume manufacturable and reliable, the three parameters of most concern to users are price, effect of component DC current consumption on talk and standby times and footprint size. GaAs components have matured remarkably into volume production during the last few years. Individual foundries providing GaAs solutions for telephone components are fabricating, packaging and testing millions of devices per month. Yields have improved, wafer diameters are increasing and die areas are decreasing, all adding to lower prices (Figure 6). Lowest priced ICs also come from using the most basic fabrication technologies, if possible – i.e. do not use via holes or thin substrates which add processing cost and likely wafer breakage. Footprint size is directly related to the types of packages being used. Very small packages (such as SOT and MSOP) have thickness' which require thin GaAs die and can only accommodate small die particularly if ground wire-bonds are needed. Power amplifiers require plastic or air-cavity plastic packages with integral heat-sinks provided by metal slug inserts or bottoms respectively.

INCREASING INTEGRATION LEVELS

There are two ways to achieve higher levels of integration – more complex ASICs and multi-chip modules (MCM's). Highly integrated ASICs, by definition, require the same technology to be used e.g. HBT, MESFET. We have already shown in Figure 5 a highly integrated AMPS/CDMA front-end chip using E/D MESFET. Other examples of such integration are the AlGaAs HBT-based transceiver IC from TRW (Kobayashi et al, 2) that combines LNA, switch and power amplifier for PHS applications within a single packaged die (Figure 7). The 1.9 GHz IC is housed in a 16-lead PSOP package with some matching provided on the PWB. The PA provides 24 dB gain at an output power of 22 dBm with an ACPR of 52 dBc at 600 kHz offset with 31% PAE. The LNA achieves 13 dB gain with a noise figure of 1.6 dB and an IP3 of 12 dBm. Special attention needs to be paid to packaging since more inputs and outputs on the chip require larger packages to accommodate the leadframe traces. These add inductance and parasitic capacitances that can lower performance and increase performance variations from lot to lot.

One of the disadvantages of using depletion mode MESFET or pHEMT transistors in power amplifier applications is that the devices require negative gate voltage. One method of overcoming this is to use a negative charge pump which can be supplied by a silicon circuit or within the GaAs IC itself (Jones, 3). Mitsubishi have incorporated a charge pump into their MESFET Personal Handy-Phone System single-chip transceiver (Nakayama et al, 4). Figure 8 shows a schematic of the circuit which consists of a power amplifier, a T/R switch, a low noise amplifier, a cascode FET downconverter and a charge pump operating from a single 3 volt supply. The IC (Figure 9) is housed in a 26 pin plastic package. Performance figures include 35% PAE from a 38 dB gain power amplifier having 21.5 dBm output power at an ACPR of 55 dBc. The receiver front-end has a gain of 22 dB with a SSB noise figure of 3.0 dB and OIP3 of +9 dBm.

Multi-chip modules afford the employment of multiple technologies within a single package. Leadless chip carriers (LCCs) are becoming a popular way of packaging of RF circuit since the method affords good RF characteristics, low inductance grounding and acceptably high thermal conductivity for heat sinking. There are also a number of other advantages to the use of LCCs – 50 ohm (or other impedance) matching can be provided within the module, higher Q components (than those on MMICs) can be employed in critical areas. Figure 10 shows a cellular power amplifier module, measuring 7mm by 7mm containing a GaAs MMIC PA as well as DC biasing and critical RF output matching components.

Higher levels of integration in MCM's are being encouraged by telephone engineers who require more RF functionality within smaller footprint areas. A PCS transmitter module, developed by Raytheon, contains 0.5-micron E/D MESFET upconverter, E/D MESFET driver amplifier and 0.5-micron pHEMT power amplifier ICs. (Figure 11). The 28-lead surface-mount module occupies a footprint area of only 120-sq. mm. The module also contains integrated thin-film, high tolerance capacitors and resistors. Overall, performance of this module is shown in Table 2. It operates from a 3.5-volt power supply and contains a silicon charge pump generating the negative voltage for the high efficiency PA.

The next challenge for LCC transmit modules is to integrate the bandpass filters that are used between the modulator and the driver amplifier as well as between the driver amplifier and the power amplifier. Presently, ceramic resonator or SAW filters are used. These can be small in footprint but cost almost as much as a GaAs MMIC power amplifier.

TRENDS IN GaAs ICs

Since price and physical size are all important for the majority of telephone components, GaAs RFIC technologists and designers are developing new process, circuit and packaging techniques to meet these requirements. The next significant requirement is to reduce battery voltage (to reduce volume and weight). Unfortunately, reductions in battery voltage increase DC current needs for power transistors resulting in larger devices and, therefore, larger ICs that translate directly to higher costs. Trade-offs are currently being studied to employ high efficiency DC-to-DC converters allowing 3.5 volt operation from 1.8 volt batteries.

There are already a number of companies that employ multi-level metallization processes (e.g. GEC-Marconi, M/A Com, Raytheon, and Triquint) to produce so-called 3D IC technology. These processes allow the employment of two or three thick metal layers to produce "stacked" inductors allowing increases in inductance per unit area by factors of greater than three. The processes do not result in undue reductions in resonant frequency or quality factor (Figure 12 (Schneiderman, 5)). In addition, thin multi-level dielectrics can be used to produce "stacked" capacitors that increase capacitance per unit area by factors of four.

Innovative RF packaging techniques are being given more attention than ever before. Whereas SOIC style packages were adequate a few years ago, smaller package footprints have now become commonplace. Leadless chip carriers are becoming a popular package scheme for power amplifier as well as for integrated transmitter and receiver modules. Considerable work is being done with chip scale packages (CSP) and ball-grid arrays (BGA). Many of the lessons learned in new high speed CPU packaging (e.g. Intel and Digital Equipment) can be applied to both small-signal and power circuit telephone applications. Some of these CSP's and BGA's are suitable for applications to over 4 GHz (Light et al, 6) as well as to higher frequencies such as those shown in Figure 13 (Panicker et al, 7). The BGA consists of brazed Cu-Ag balls attached to an alumina substrate with thru' substrate vias. The GaAs IC chips can be mounted either conventionally i.e. backside down with wire-bonds or flipped over with their own solder bumps negating the need for wire-bonds. CSP where solder bumps are employed together with an underfill and plastic seal on the "back" of the die is the ultimate in allowing chips to be pre-tested prior to insertion in MCM's.

CONCLUSIONS

GaAs RFICs have made considerable impact on the low-price, quality and performance of mobile telephone handsets for a range of standards during the last few years. The performance and integration levels of such components are increasing as well as meeting the required price goals. A summary of recent GaAs RFIC PCS component performances is given in Table 3. This paper has shown that GaAs RFICs are used in all RF sections of digital telephones, particularly for PCS frequencies, since they provide advantages of higher performance and lower DC current consumption when compared with silicon technologies. Examples of GaAs ICs have be given from leading companies displaying state-of-the-art performances leading to the conclusion that fully integrated transmit/receive functions can provide substantial reductions in price and size during the next few years.

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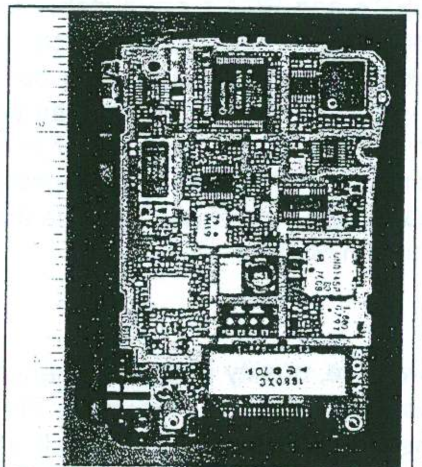

Figure 1. RF Section of PCS CDMA Mobile Telephone (Sony)

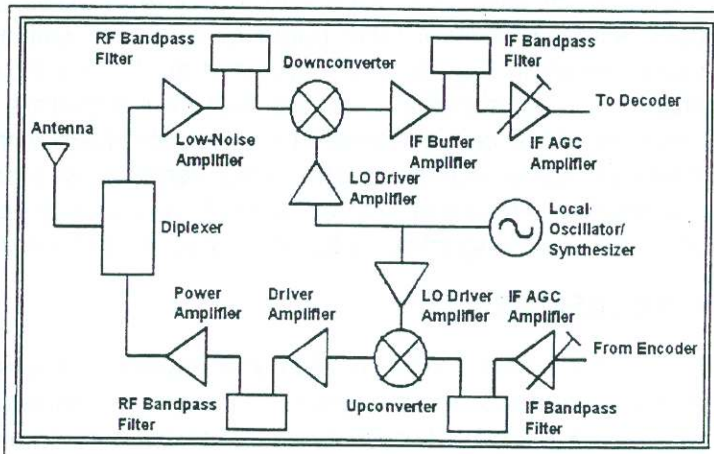

Figure 2. Typical Cellular Telephone RF Schematic

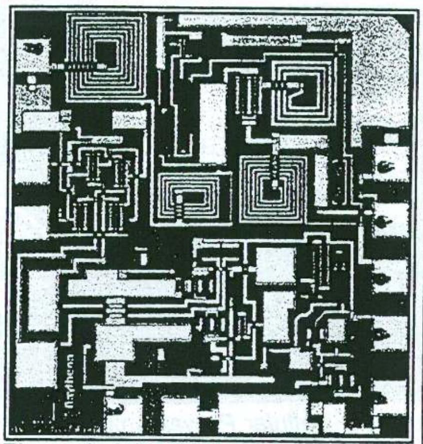

Figure 3. MESFET PCS Upconverter MMIC (Raytheon)

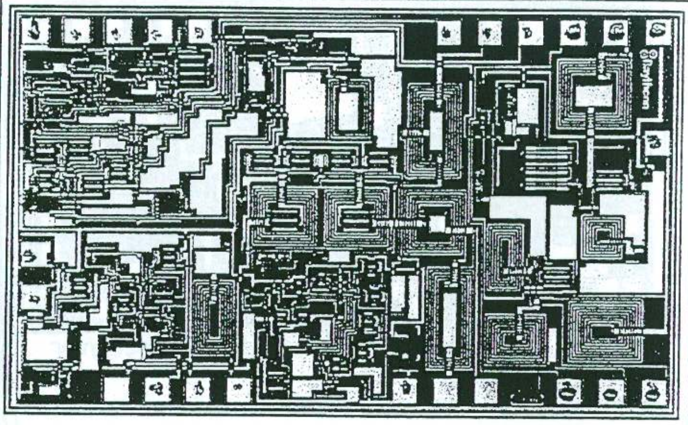

Figure 5. Dual Mode Cellular Analog/CDMA Receiver MMIC (Raytheon)

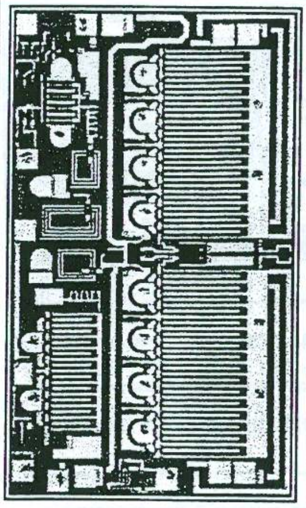

Figure 4. pHEMT PCS CDMA Power Amplifier MMIC (Raytheon)

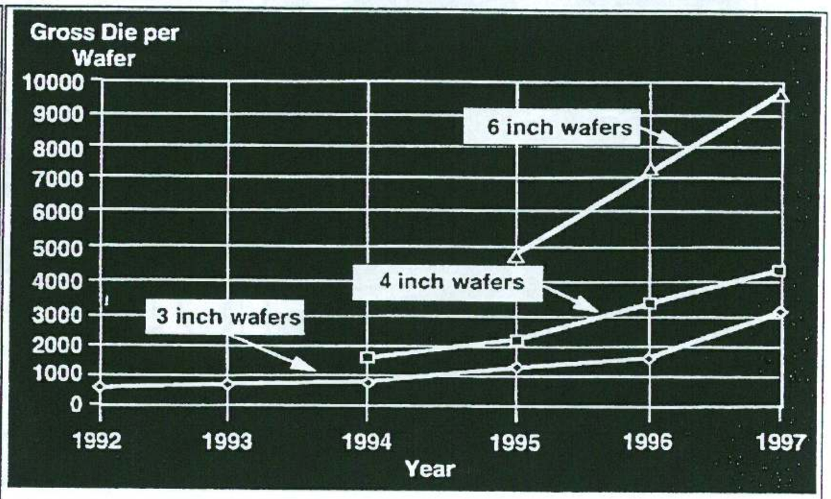

Figure 6. Effect of Die Shrinkage and Wafer Diameter on Gross Die per Wafer

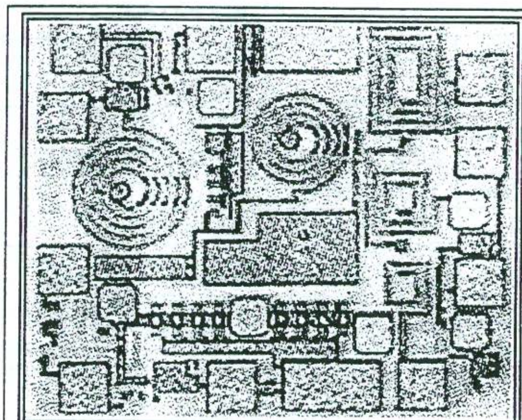

Figure 7. Single Chip HBT Transceiver MMIC (TRW)

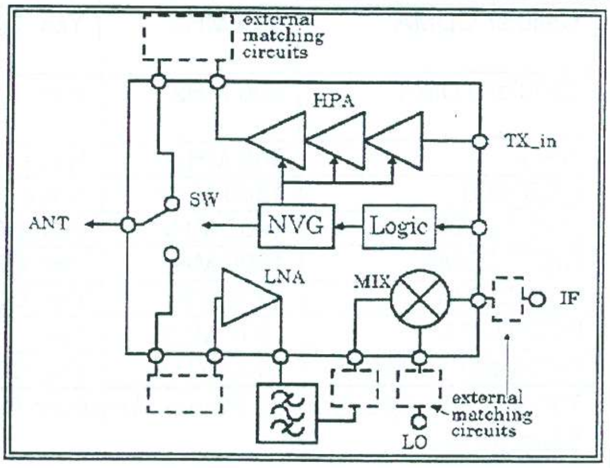

Figure 8. Schematic of Single Chip PHS MESFET Transceiver (Mitsubishi)

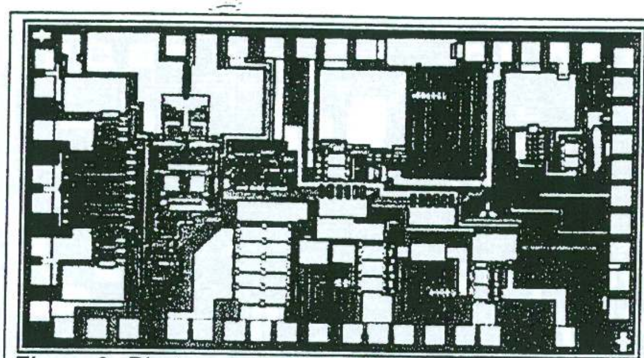

Figure 9. Photograph of MESFET PHS Transceiver MMIC (Mitsubishi)

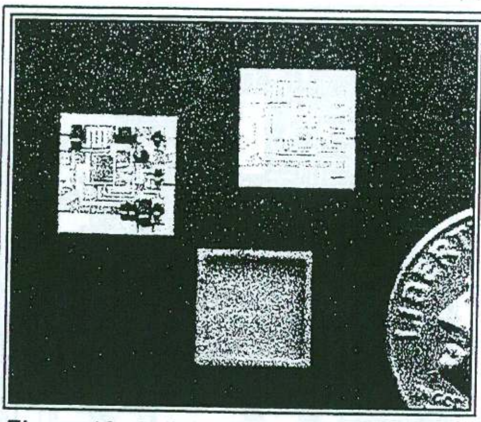

Figure 10. Cellular Power Amplifier Module (Raytheon)

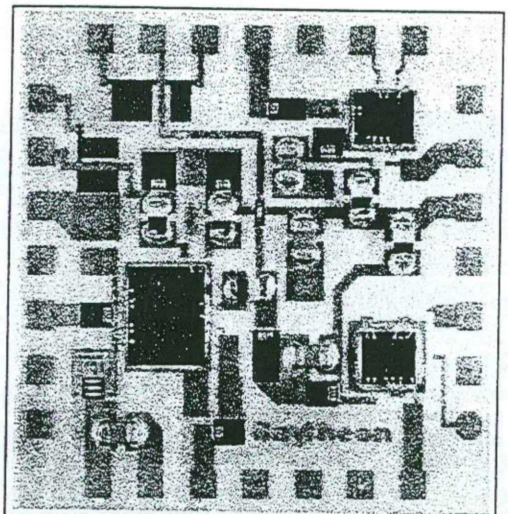

Figure 11. PCS Transmit Module (Raytheon)

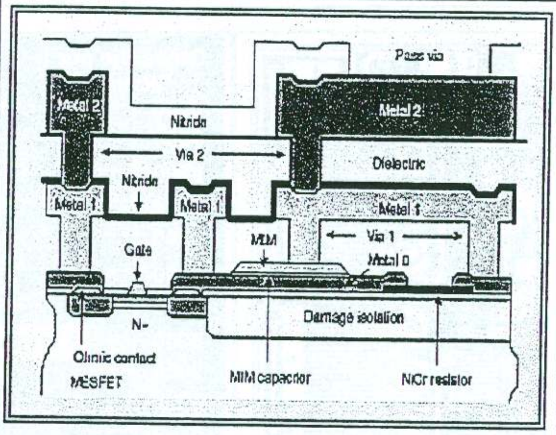

Figure 12. Multi-Level Metallization GaAs IC Process (Triquint)

Standard	*Frequency (approx.)*	*Linearity*	*Output Power, mW*	*"Popular" Technologies*
AMPS	900 MHz	None	1250, CW	Si BJT, Si LDMOS
Cellular CDMA	900 MHz	Yes, OQPSK	640, CW	GaAs FET, pHEMT, Si LDMOS
Cellular TDMA	900 MHz	Yes	1550	GaAs FET, Si LDMOS
GSM	900 MHz	None	2820, pulsed	GaAs FET, Si BJT
DCS1800	1800 MHz	None	2000, pulsed	GaAs FET, pHEMT
PHS TDMA	1900 MHz	Yes, DQPSK	100, pulsed	GaAs FET
DECT TDMA	1900 MHz	Yes, GFSK	250, pulsed	GaAs FET
PCS CDMA	1900 MHz	Yes, OQPSK	640, CW	GaAs pHEMT, HBT
PCS TDMA	1900 MHz	Yes	1100, pulsed	GaAs pHEMT, HBT
Globalstar CDMA	1600 MHz	Yes, OQPSK	640, CW	GaAs FET, HBT

Table 1. Comparison of Power Amplifier Requirements for Various Mobile telephone Standards

Parameter	Performance
IF Frequency	130 MHz
LO Frequency	1750 MHz
LO Input Power	- 6 dBm
Overall Gain	43 dB
Overall Noise Figure	14 dB (High Gain) 19 dB (Low Gain)
Gain Control	15 dB
Output Power (CDMA)	28 dBm
Input IP3 (High Gain)	- 4 dBm
ACPR1 @ 1.25 MHz Offset	49 dBc
ACPR2 @ 2.25 MHz Offset	65 dBc
Image Rejection	60 dBc
IF to RF Isolation	60 dB
LO to RF Leakage	-50 dBm min.
LO Harmonics @ RF P_{OUT}	-50 dBm min.
DC Voltages and Currents (at P_{OUT}) DC Voltages and Currents at Idle	3.0 V @ 68 mA 3.5 V @ 550 mA 3.0 V @ 53 mA 3.5 V @ 140 mA
Package	28 Lead Quad LCC

Table 2. Performance of Complete LCC PCS Transmit Module (Raytheon)

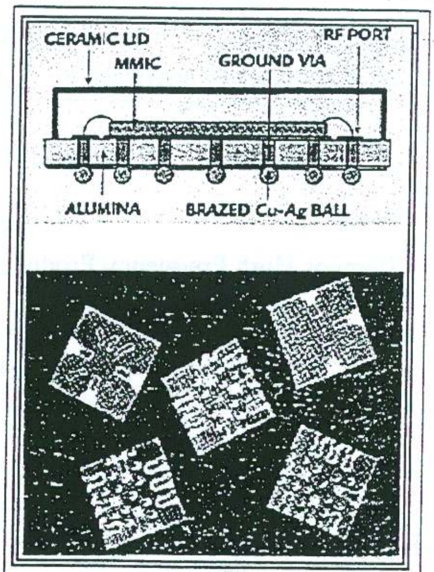

Figure 13. ViaPak™ Ball Grid Array (Micro Substrates Corp.)

Function	*Performance Highlights*	*Company*
Power Amplifiers		
GaAs MESFET	Gain = 30 dB; P_{OUT} = 28.5 dBm; PAE = 35%; ACPR meets IS-95 and IS-136; Voltage = 3 volts	Celeritek
	Gain = 25 dB; ACPR = 45 dBc; PAE = 40%; P_{OUT} = 29 dBm; Voltage = 3.5 volts	Siemens
GaAs pHEMT	Gain = 30dB; ACPR = 49 dBc; PAE = 38%; P_{OUT} = 29 dBm; Voltage = 3.5 volts	Raytheon
AlGaAs HBT	Gain = 18.5 dB; ACPR = 45 dBc; PAE = 37% P_{OUT} = 28.5 dBm; Voltage = 4.8 volts	RFMD
Driver Amplifiers		
GaAs MESFET	Gain = 16 dB; P_{1dB} = 17 dBm; NF = 4 dB; Voltage = 5 volts @ 85 mA	Triquint
	Gain = 25 to 30 dB; Gain Step = 15 to 20 dB; NF = 4 dB; P_{OUT} = 8 dBm; ACPR = 60 dBc; Voltage = 3 volts; Current = 50 mA	Raytheon
Downconverters @ 3 volts		
GaAs MESFET	LNA: Gain = 17 dB; NF = 2.5 dB Mixer: Gain = 8 dB; NF = 10 dB	Motorola
	LNA: Gain = 12 dB; NF = 1.7 dB Mixer: Gain = 6 dB; NF = 6 dB	Raytheon
	Mixer: Gain = –6 dB; NF = 6 dB	Siemens
Upconverters @ 3 volts		
GaAs MESFET	Gain = 15 dB; P_{1dB} = 0 dBm; Current = 25 mA	Motorola
	Gain = – 0.4 dB; NF = 11 dB; ACPR = 62 dBc; Current = 24 mA	Qualcomm
	Gain = 0 dB; NF = 12 dB; ACPR = 60 dBc; Current = 20 mA	Raytheon

Table 3. Summary of Recent GaAs RFIC Performances for PCS/CDMA Applications (Information available as of May 1998)